Measuring Jet Constituent Yields in 5.02 TeV Pb--Pb Collisions Using Jet-Hadron Correlations with ALICE

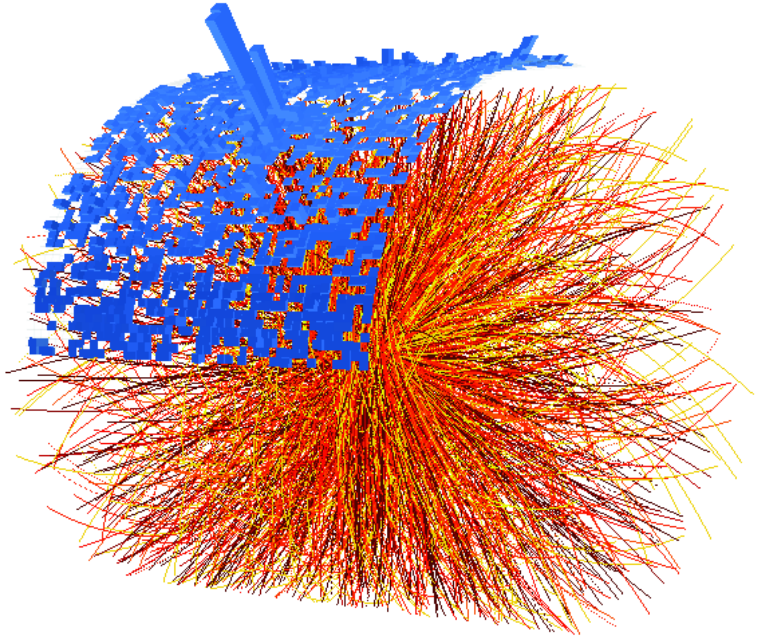


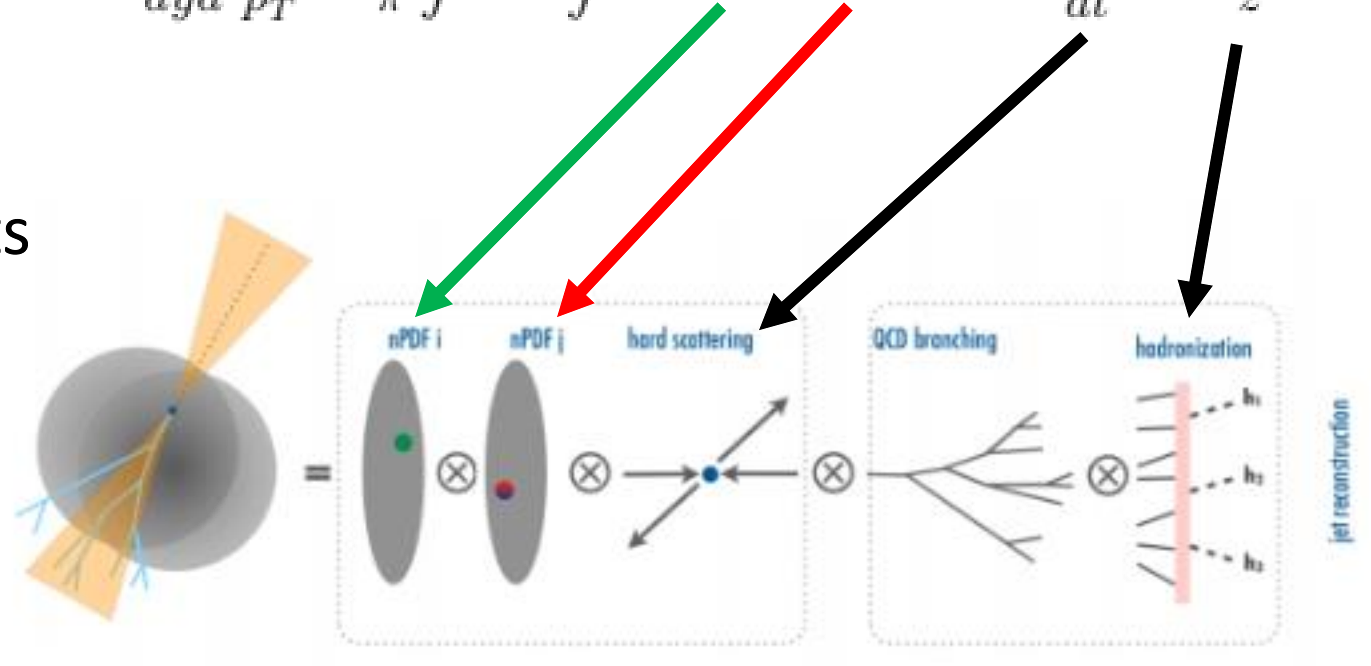
Figure taken from https://cds.cern.ch/record/1648854/plots

Presented by Charles Hughes on behalf of the ALICE Collaboration

PHYSICS MOTIVATION

- Quark Gluon Plasma (QGP) - hot, thermalized partonic state of matter
- Wish to study energy loss of hard probes produced in QGP – using jets
- Energy loss an important tool for understanding QGP transport properties

$$\frac{d^3\sigma^h}{dy d^2 p_T} = \frac{1}{\pi}\int dx_a \int dx_b f_a^A(x_a) f_b^B(x_b) \frac{d\sigma_{ab\to cX}}{d\hat{t}} \frac{D_c^h(z)}{z}$$



PHYSICS MOTIVATION CONTINUED

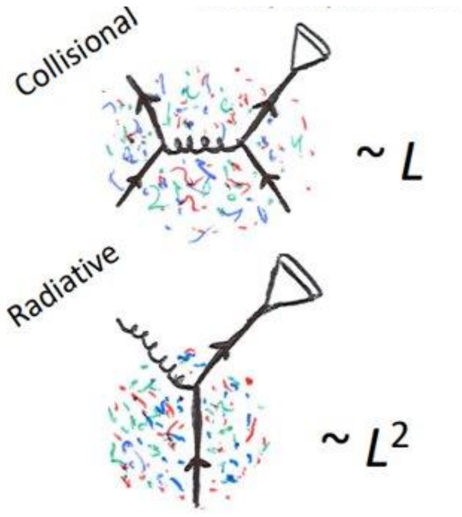
- Energy loss in QGP medium expected to have a dependence on path length

- Path length dependence
  - Collisional -> L
  - Radiative -> L^2

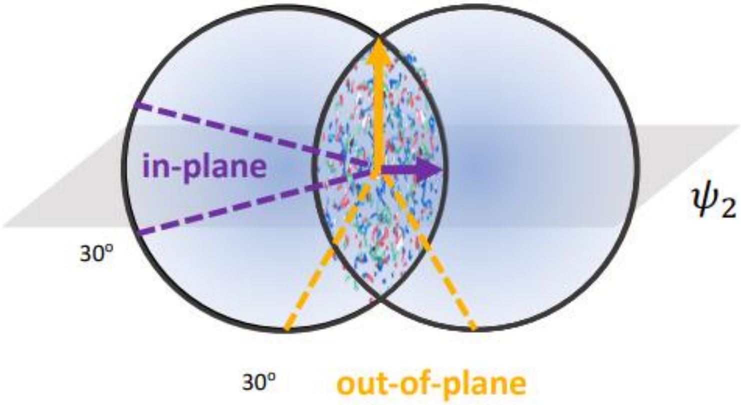
*Under simplifying assumptions

- Relative Energy Loss
  - More medium vs. less medium

Assuming a static medium in the weakly coupled limit

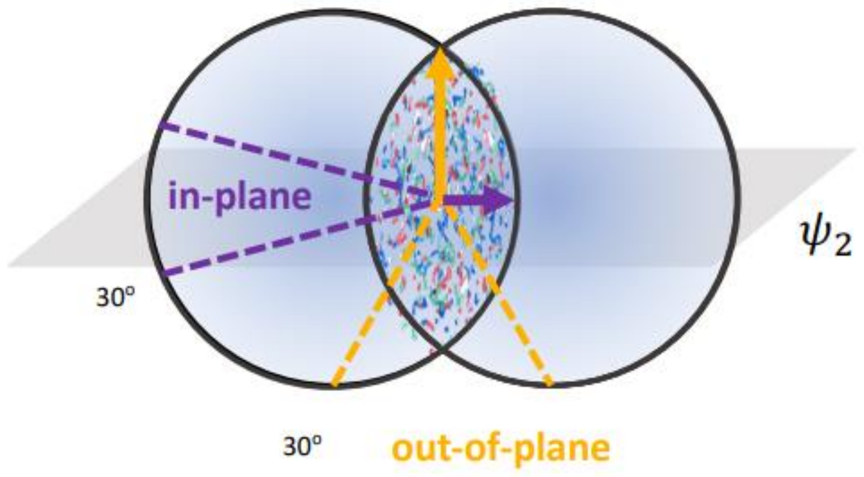


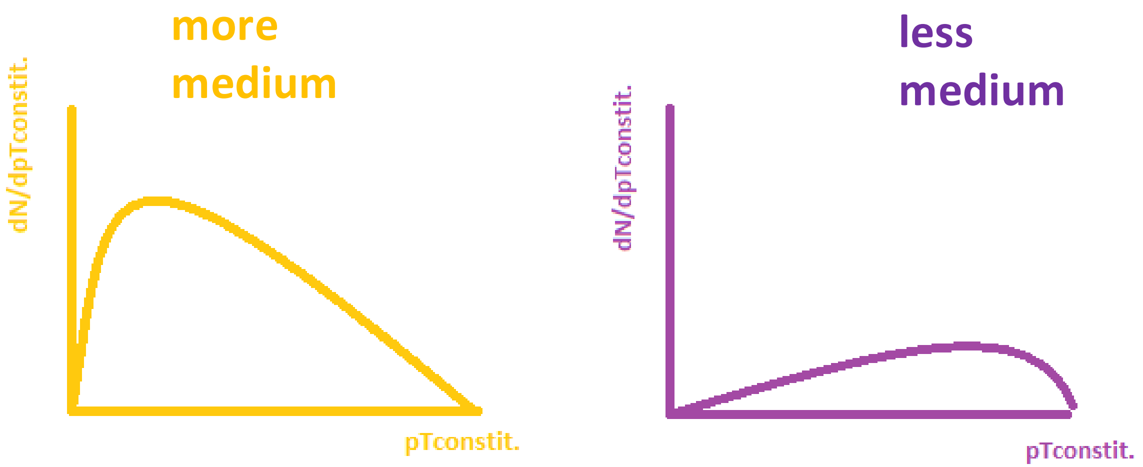
M. Djordjevic, et. al., Phys. Rev. C, 2019.



PHYSICS OBSERVABLE – JET CONSTITUENT YIELDS

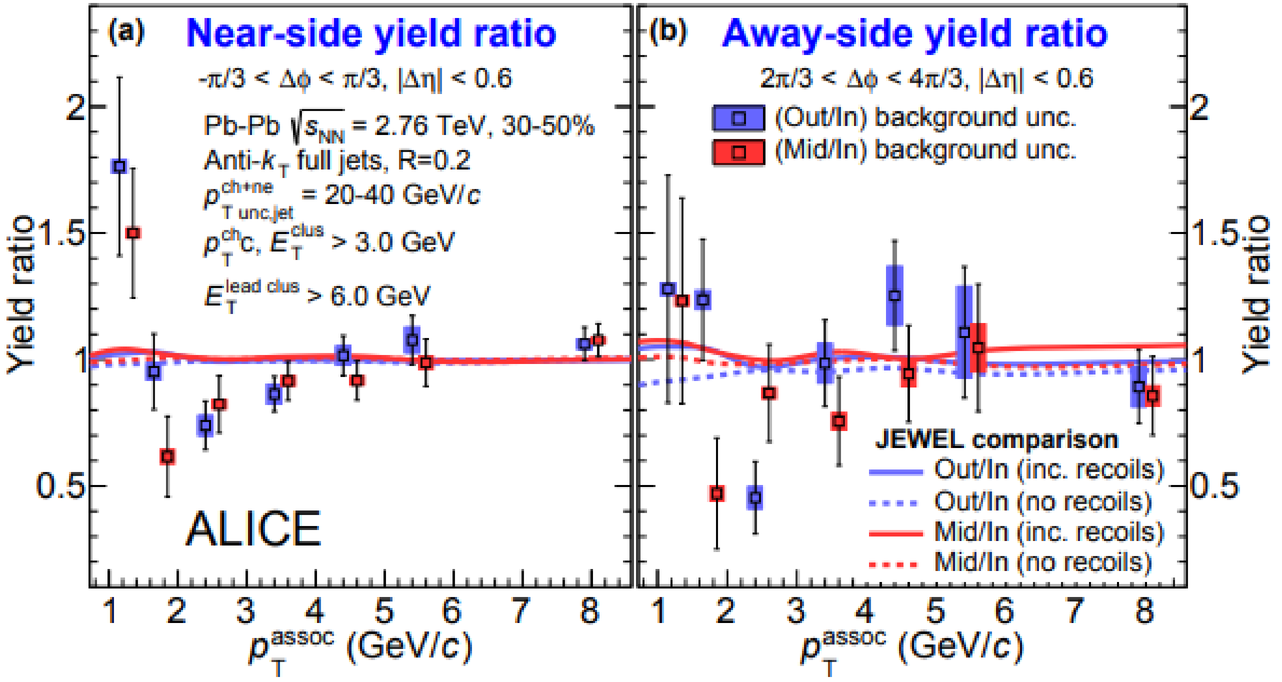
- $p_T^{constit.}$ – momentum of jet constituent hadrons
- $dN/dp_T^{constit.}$ or $Y(p_T^{constit.})$ – distribution of constituent momentum
- Is jet composed of many soft hadrons or few soft hadrons and some high p_T hadrons ?
- Can investigate how $Y(p_T^{constit.})$ depends on jet orientation to event plane





JET CONSTITUENT YIELDS – MODELS/PREVIOUS

- Model Expectation predicts excess of particles at low p_T (small effect)
- Ex. **[*Phys.Rev.C* 101 (2020) 6, 064901]** - "Jet-hadron correlations measured relative to the second order event plane in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV"
- **Can use Jet-hadron correlations to determine**



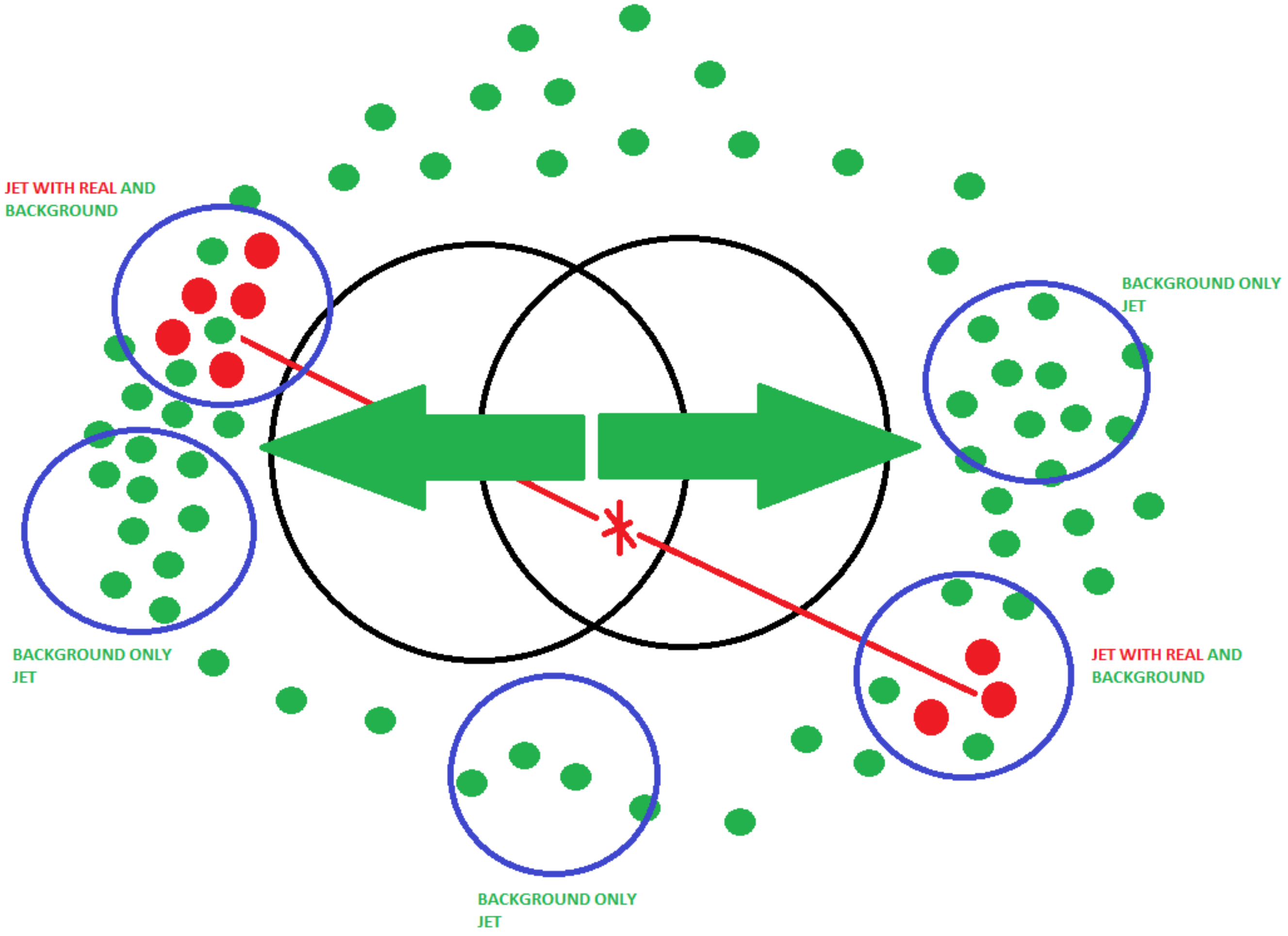
ALICE

JET BACKGROUND

- Simplified picture
  - **Signal/Real particles** from hard scatterings
  - **Background particles** from soft processes

- **Jets** with **combinatorial background**

- **Jets composed of entirely combinatorial background**



ALICE

JET HADRON CORRELATIONS

- Procedure
  1. Use algorithm to find jet
  2. Calculate $\Delta\varphi = \varphi_{jet} - \varphi_{hadron}$
  3. Calculate $\Delta\eta = \eta_{jet} - \eta_{hadron}$

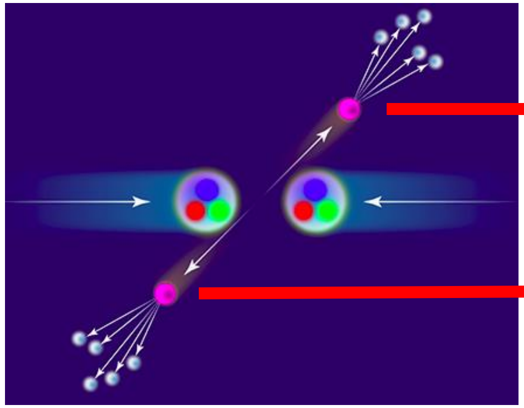
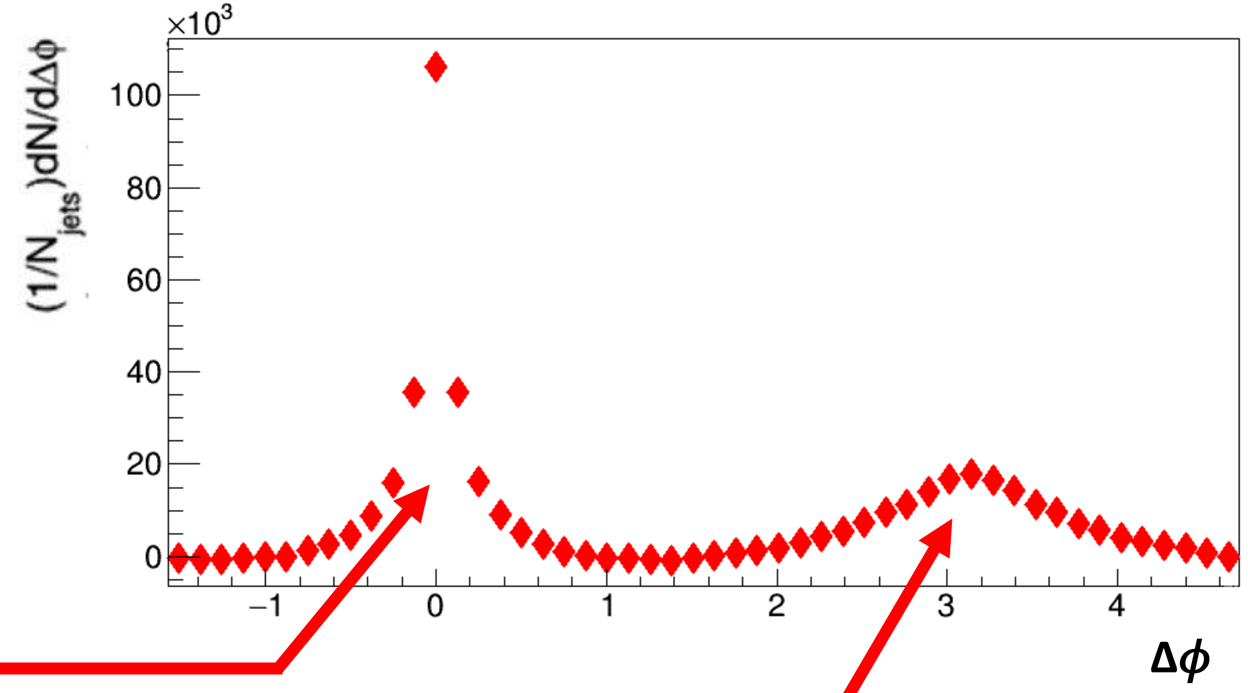
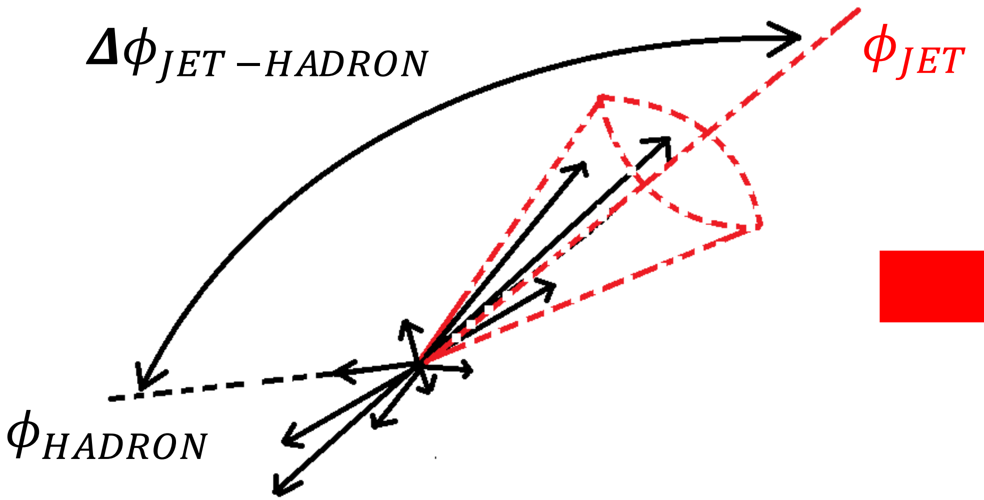


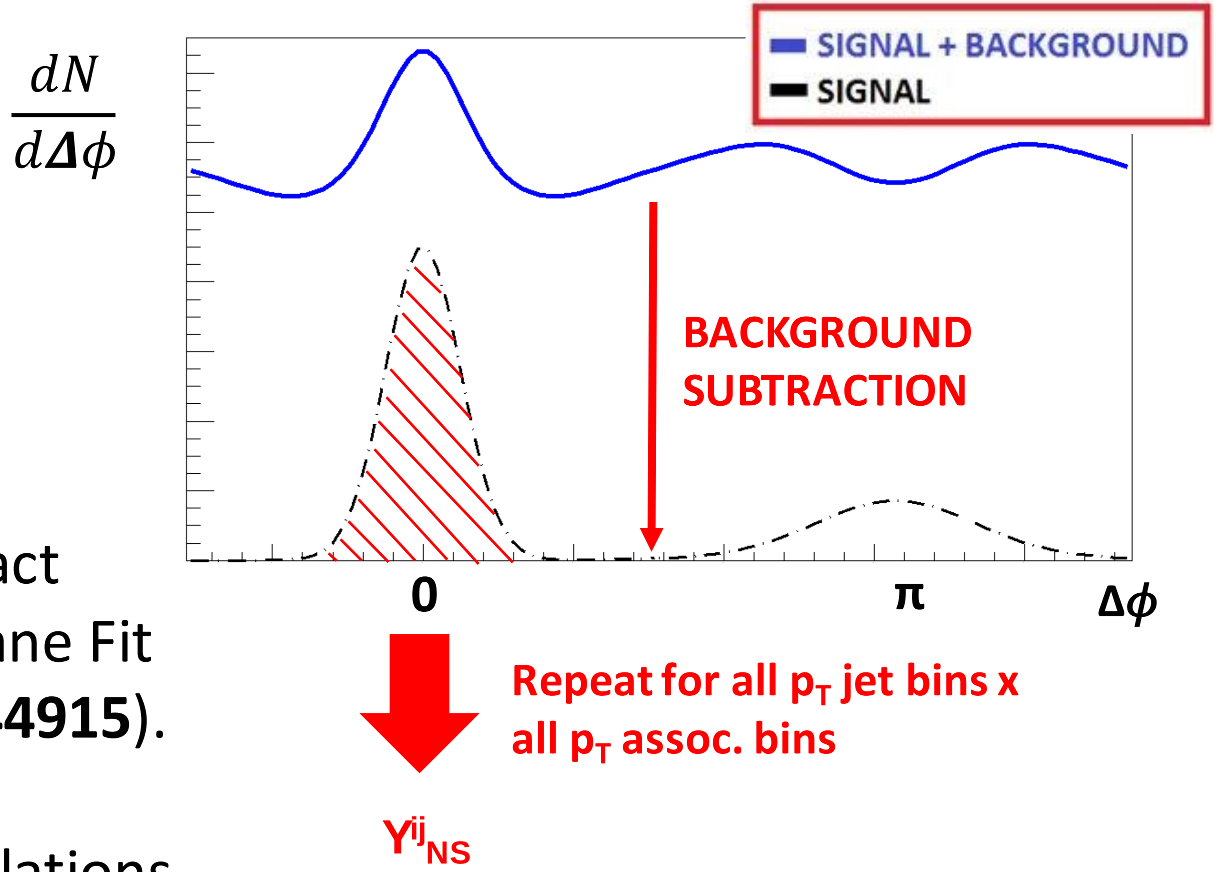
Image Credit: APS website: "Viewpoint: The Stopping Power of Hot Nuclear Matter" – Cristina Manuel 09/2014



Reveals Jet Near Side and Away Side Structure !

BACKGROUND SUBTRACTION w/ CORRELATIONS

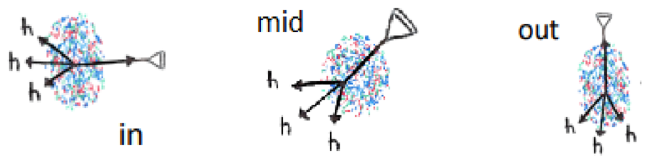




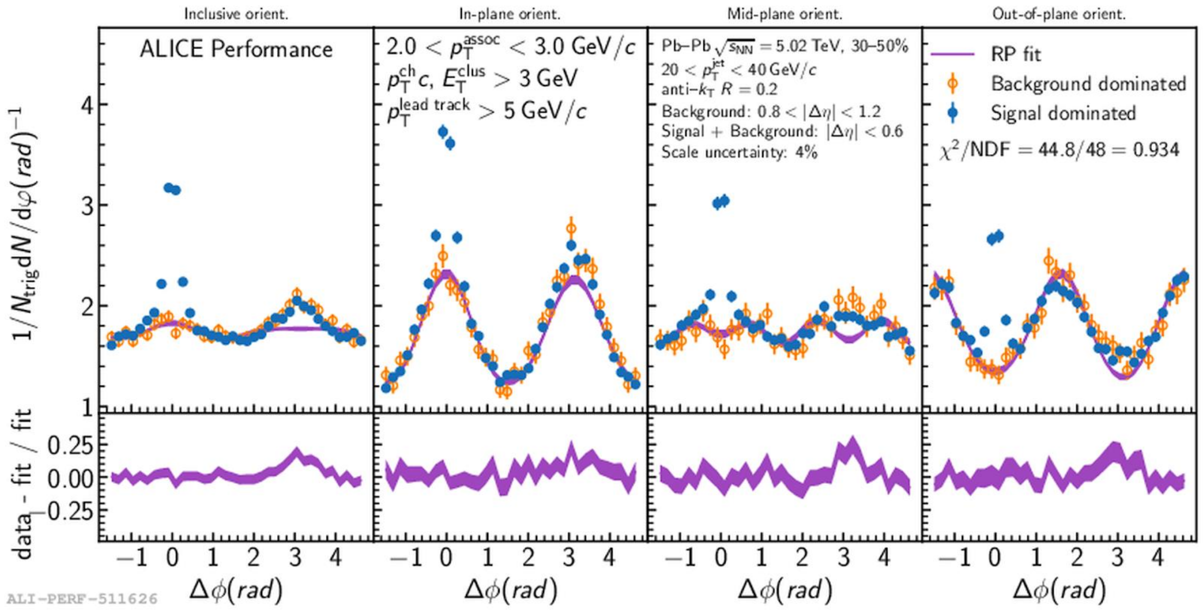
- Use jet-hadron correlations in Pb+Pb to subtract underlying event on average with Reaction Plane Fit (RPF) Method (**Phys. Rev. C93 (2016) no. 4, 044915**).
- Use yields (Y^{ij}_{NS} , Y^{ij}_{AS}) from subtracted correlations to get information on the Fragmentation Function

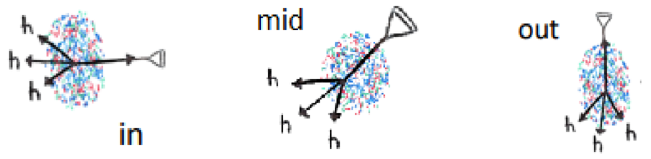
METHOD

Illustrations from Cailtin Beattie



- Important Detail
  - RPF Method gives 4x2 yields for each $p_T^{assoc.}$ (i) and p_T^{jet} (j) bin (near and away)
  - Inclusive Yield
  - In-plane Yield: $|\varphi - \Psi_2| > 30°$
  - Mid-plane Yield: $30° < |\varphi - \Psi_2| < 60°$
  - Out-of-plane Yield: $60° < |\varphi - \Psi_2| < 90°$
  - **Event plane dependent yields for jet constit. yields**





ALICE DETECTOR

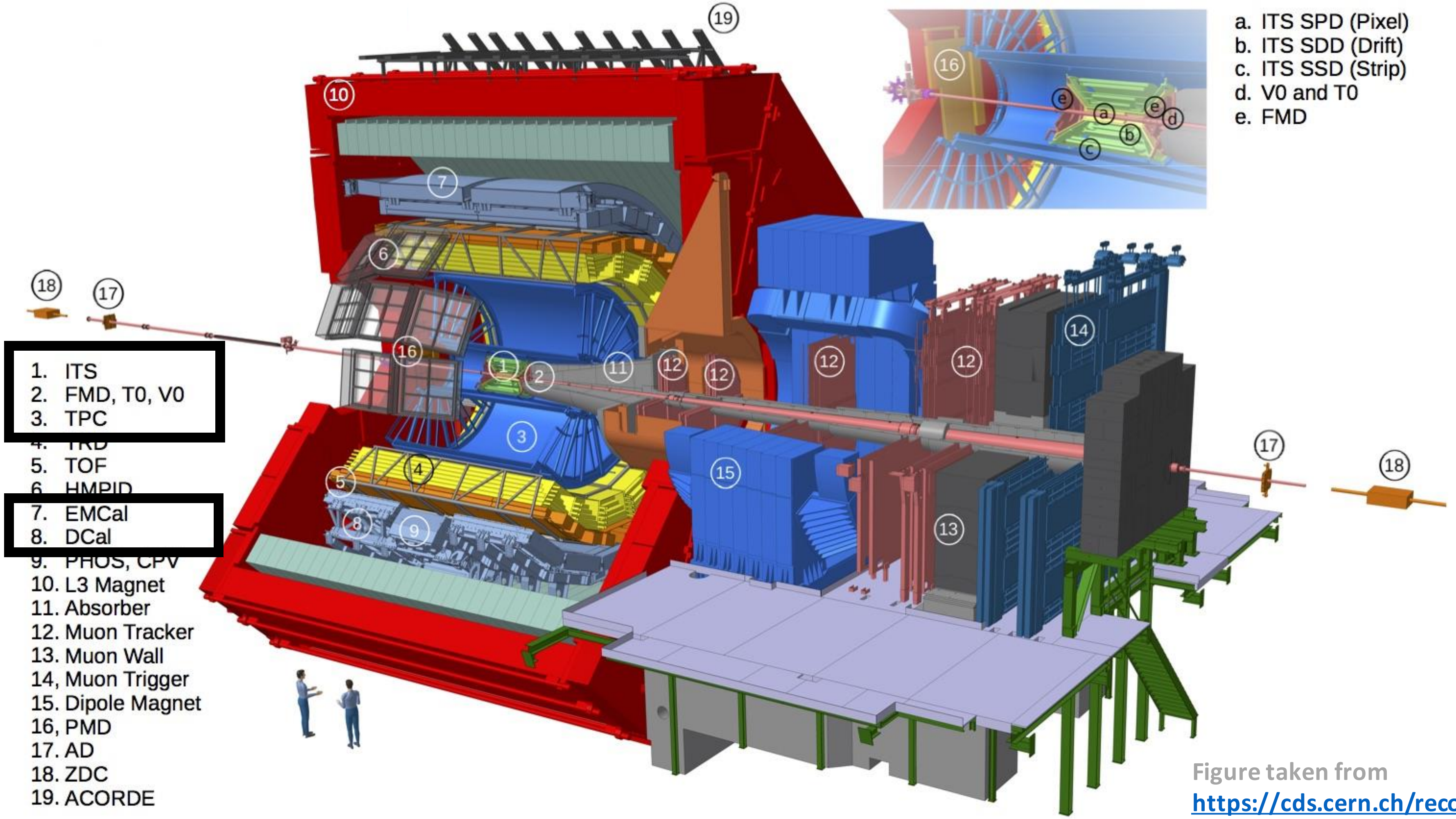


Figure taken from https://cds.cern.ch/record/2263642

ITS: Vertexing, Charged Tracking

V0: Event Plane

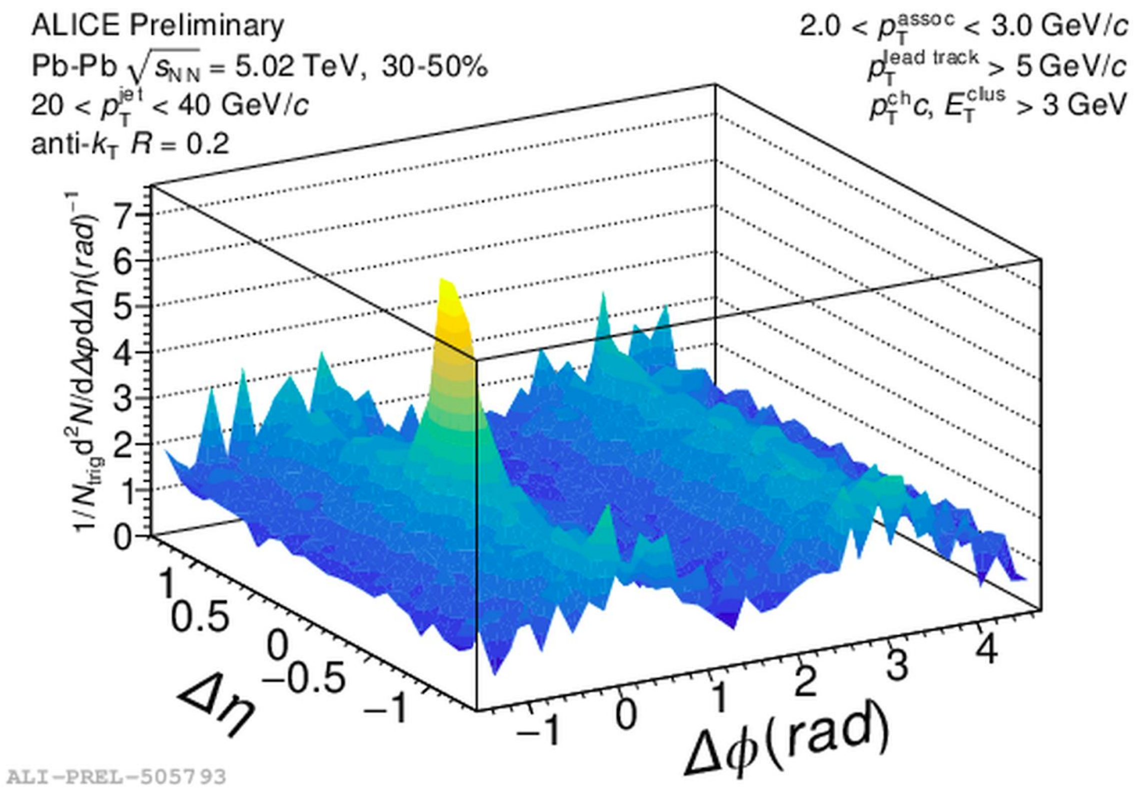
TPC: Charged Tracking

EMCAL + DCAL: Neutral Energy

DATA ANALYSIS – CORRELATION FUNCTIONS

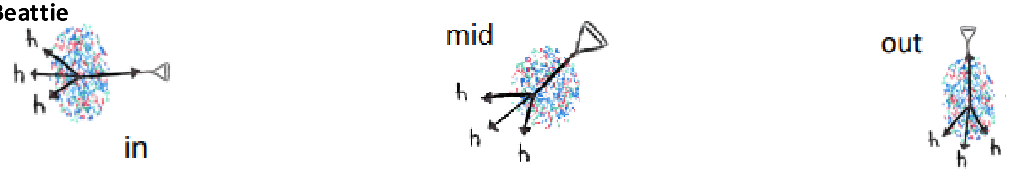
- Corrected correlation function
  - 20-40 GeV Jet p_T
  - 2.0 – 3.0 GeV associated particle p_T
  - R = 0.2 anti-k_T, charged + neutral
  - Semi-Central
  - In-Plane Jets

  - Corrected for single track reconstruction efficiency & acceptance effects

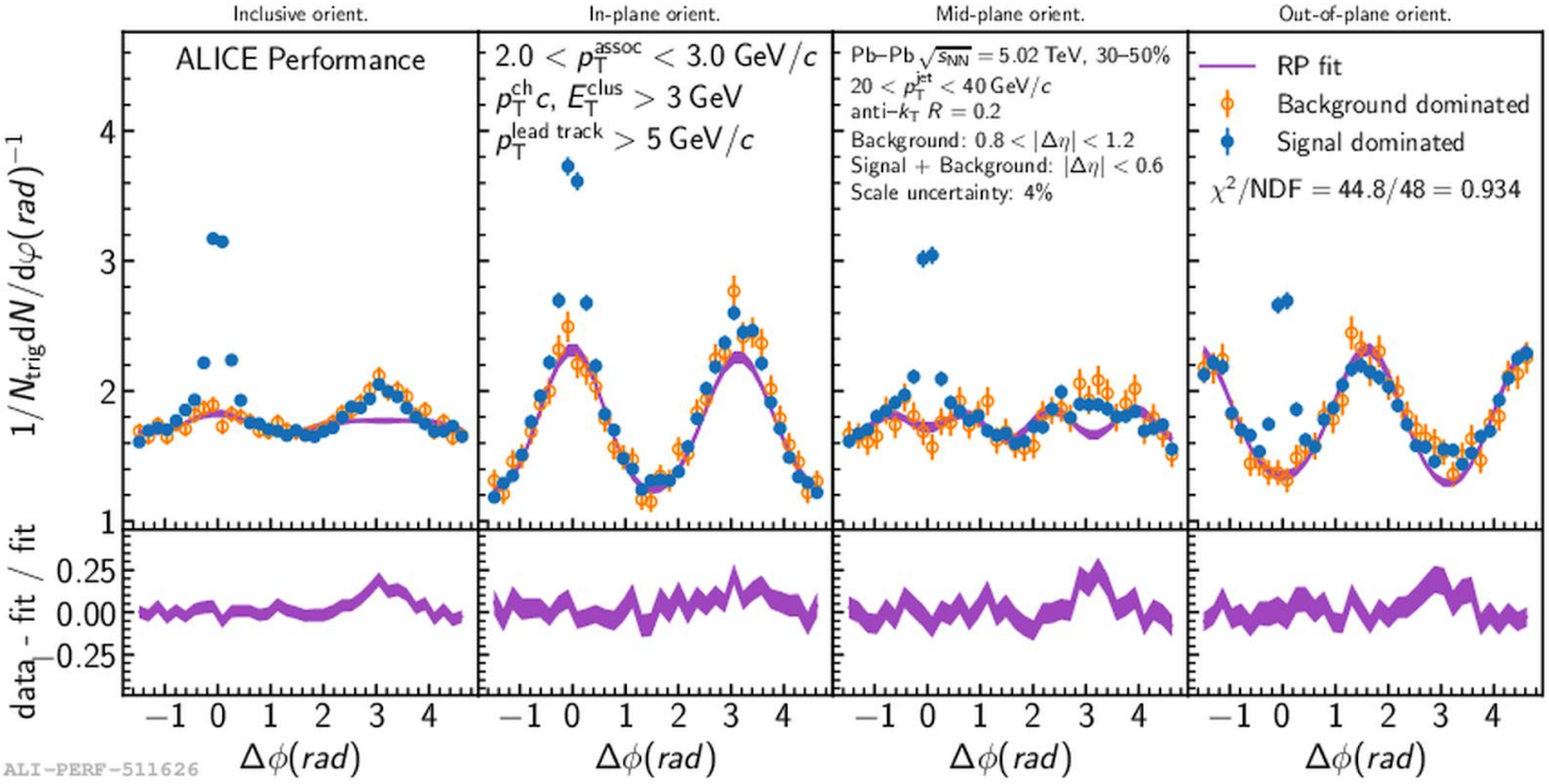


DATA ANALYSIS - FITS

Illustrations from Cailtin Beattie

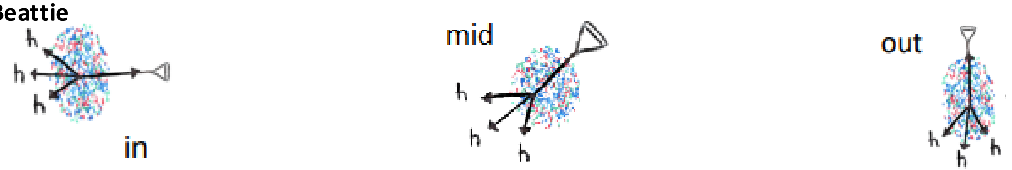


- Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
- 30 – 50 %
- p_T^{jet} : 20-40 GeV/c
- $p_T^{assoc.}$: 2-3 GeV/c
- Fit on near side only
  - **$|\Delta\varphi| < \pi/3$**
  - **$0.8 < |\Delta\eta| < 1.2$**
- Simultaneous near side fit for in, mid, and out

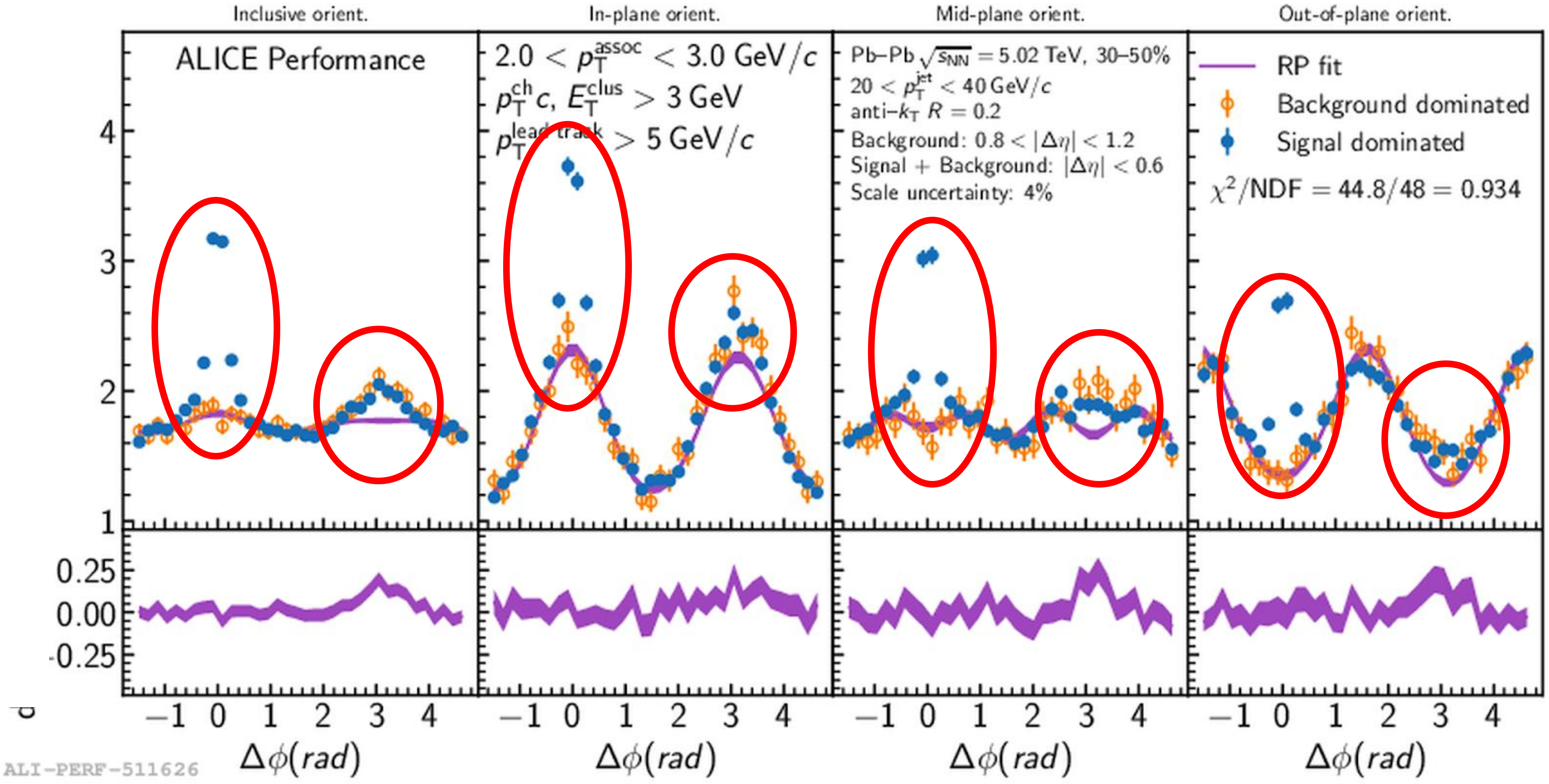


DATA ANALYSIS - FITS

Illustrations from Cailtin Beattie



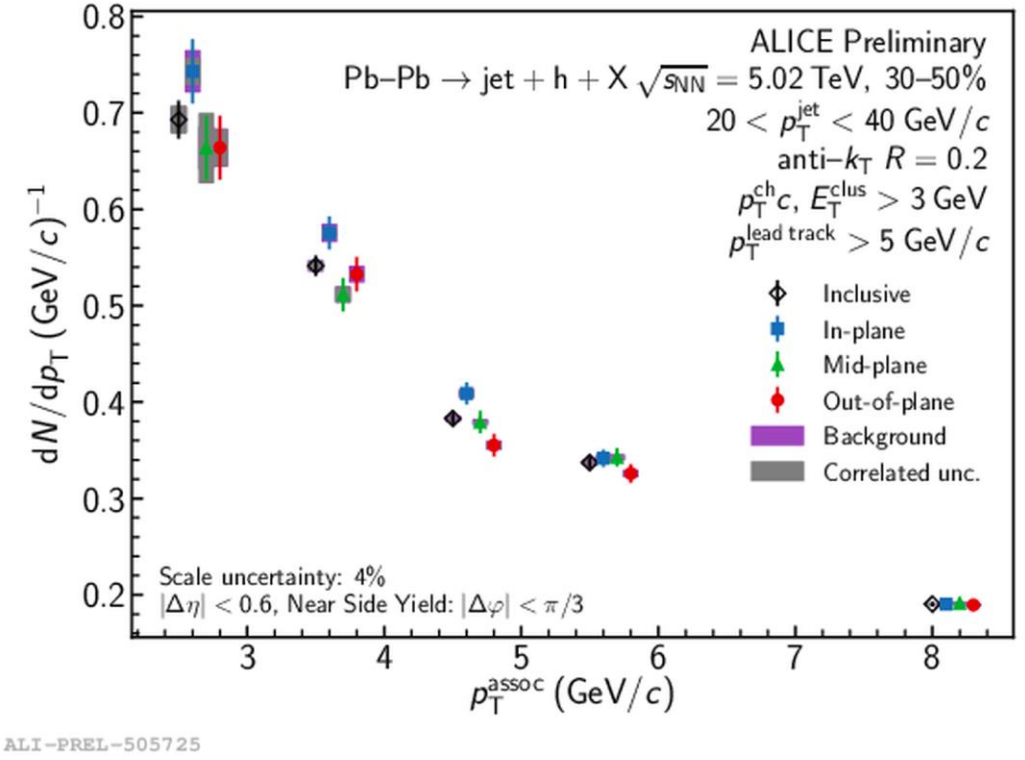
- Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
- **Take difference between blue points and purple curve (reaction plane fit), then integrate near and away side peaks**
- Simultaneous near side fit for in, mid, and out



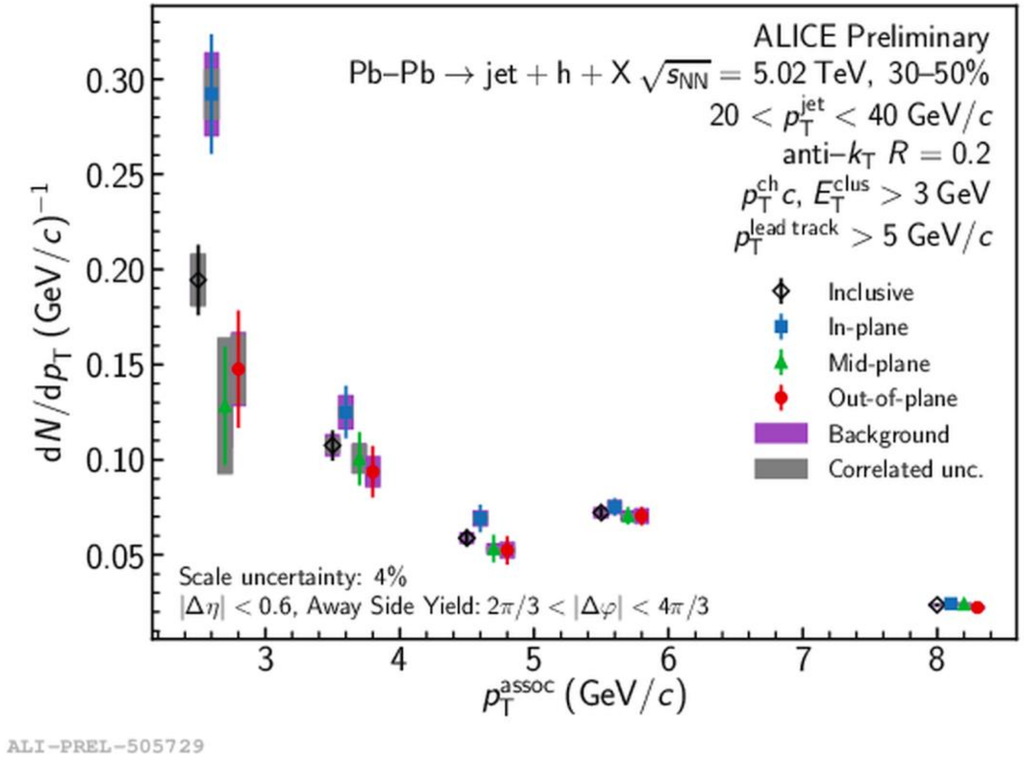
RESULTS – CONSTITUENT YIELDS

Illustrations from Cailtin Beattie

In-Plane: $|\varphi_{jet} - \Psi_2| < \pi/6$ | Mid-Plane: $\pi/6 < |\varphi_{jet} - \Psi_2| < \pi/3$ | Out-of-Plane: $\pi/3 < |\varphi_{jet} - \Psi_2| < \pi/2$



In-Plane: $|\varphi_{jet} - \Psi_2| < \pi/6$ | Mid-Plane: $\pi/6 < |\varphi_{jet} - \Psi_2| < \pi/3$ | Out-of-Plane: $\pi/3 < |\varphi_{jet} - \Psi_2| < \pi/2$



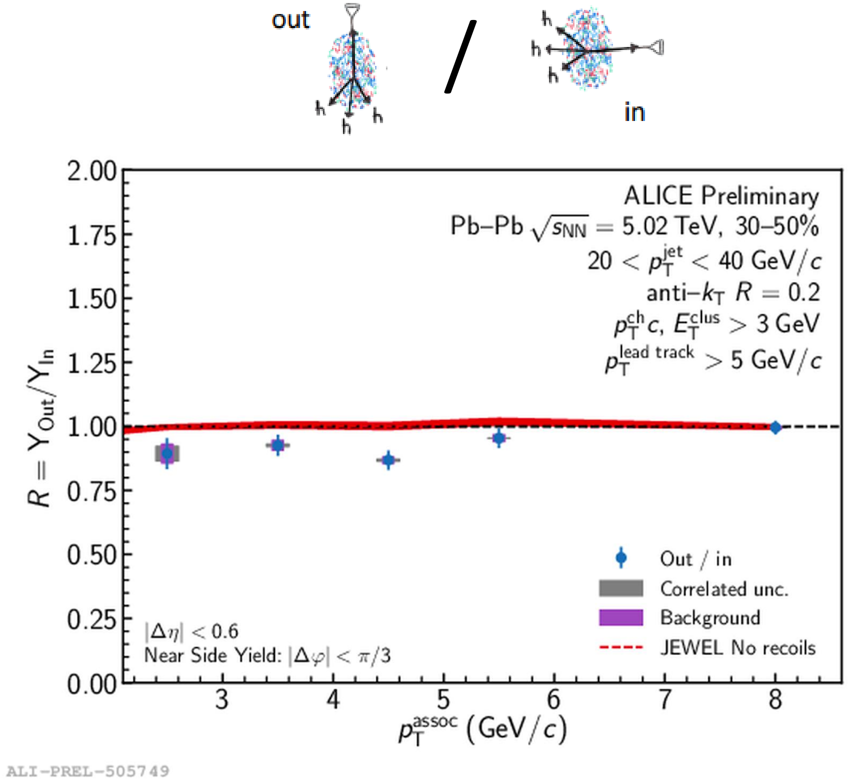
Near-side yields (NS)
- Within uncertainties, no ordering

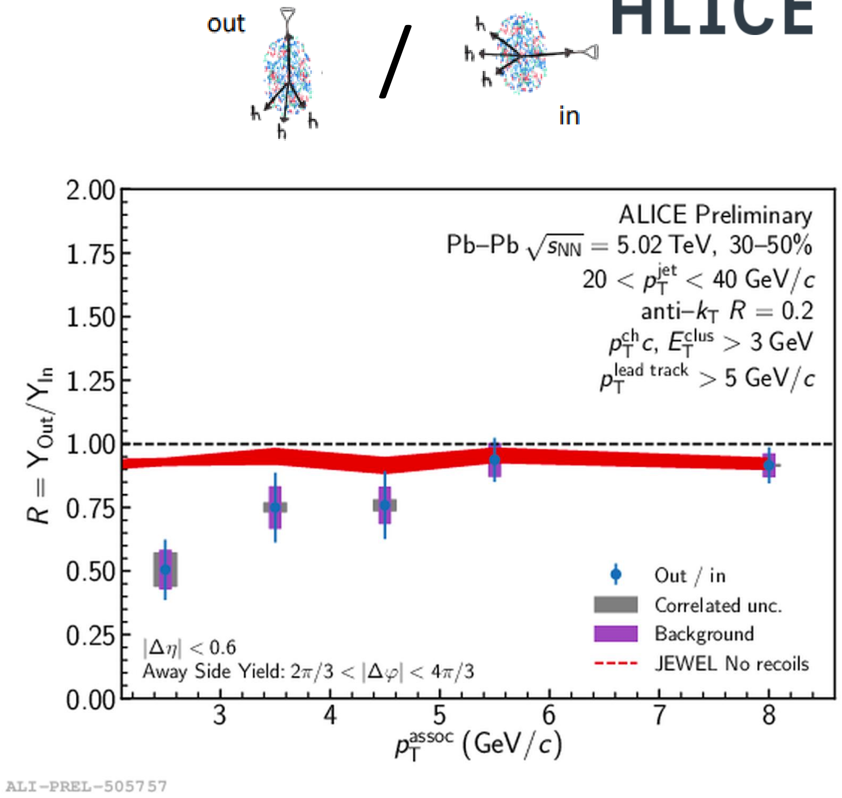
Away-side (NS)
- Some ordering in lowest $p_T^{assoc.}$ bin (< 3σ)

RESULTS – YIELD RATIOS

- Compare yields to each other (ratios)
  - Searching for event plane dependence
  - **Out**/**in** for NS and AS
  - Within uncertainties – no EP dependence
  - 3σ from unity in $2 < p_T^{assoc.} < 3$ GeV/c AS
- Compare yields to simulation (JEWEL without recoils)
  - Within uncertainties – agreement

Illustrations from Cailtin Beattie





ALICE

Conclusions and Outlook

- Constituent yields above 2 GeV/c do not show clear event plane dependence
  - Hints at difference in the 2-3 GeV/c bin
  - Not clear if path length dependence is dominant physical effect
    - (event shape and jet-by-jet fluctuations may also play a role)

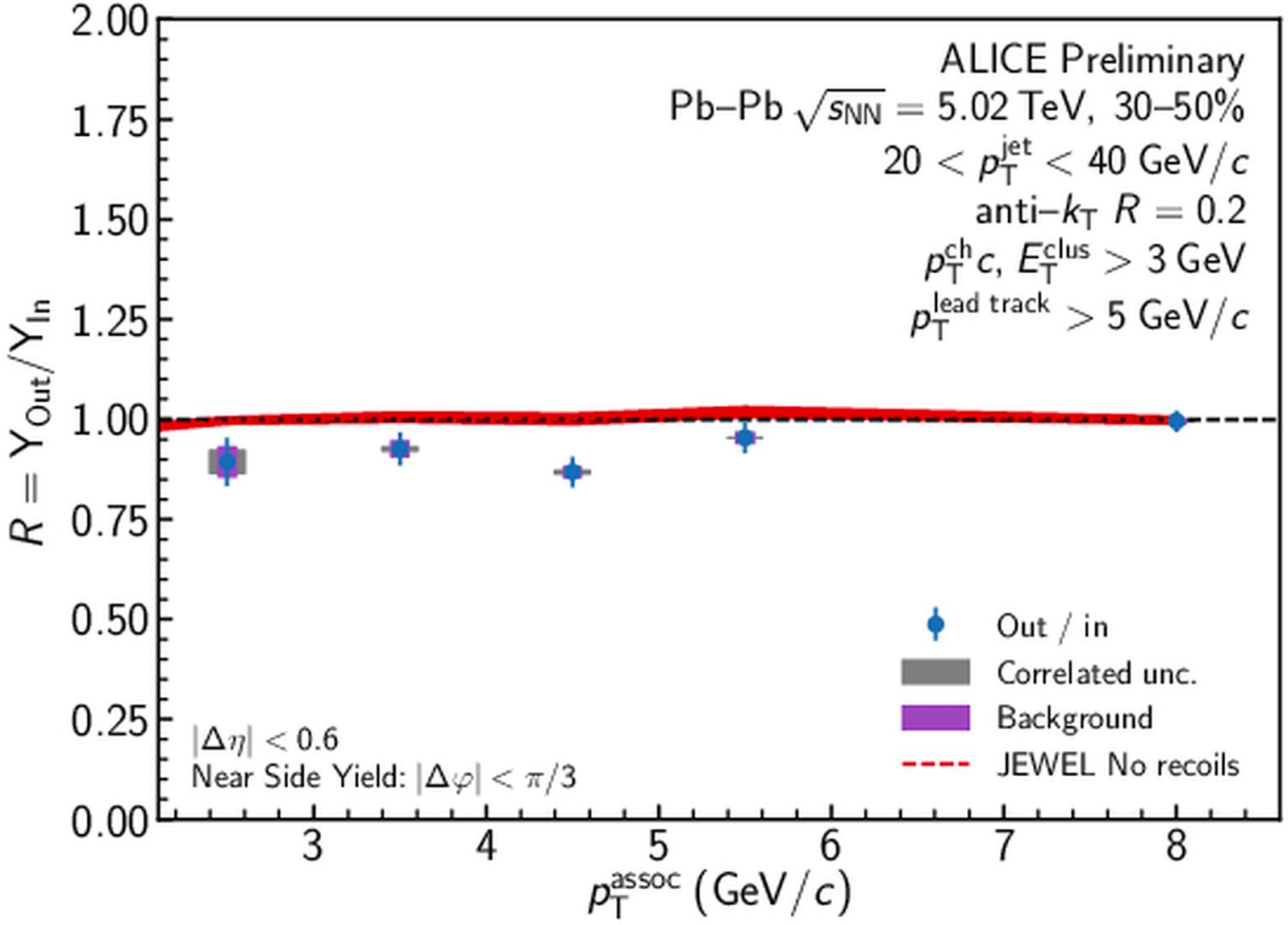
- Future Work
  - Extend analysis below 2 GeV/c in $p_T^{assoc.}$ (current work in progress)
  - Correct for jet energy scale resolution (current work in progress)
  - Unfold yields for low jet p_T fragmentation functions (model studies show promise)
  - Can use this technique for constituent yields in future detectors (sPHENIX)

Backup

Backup – Analysis Details

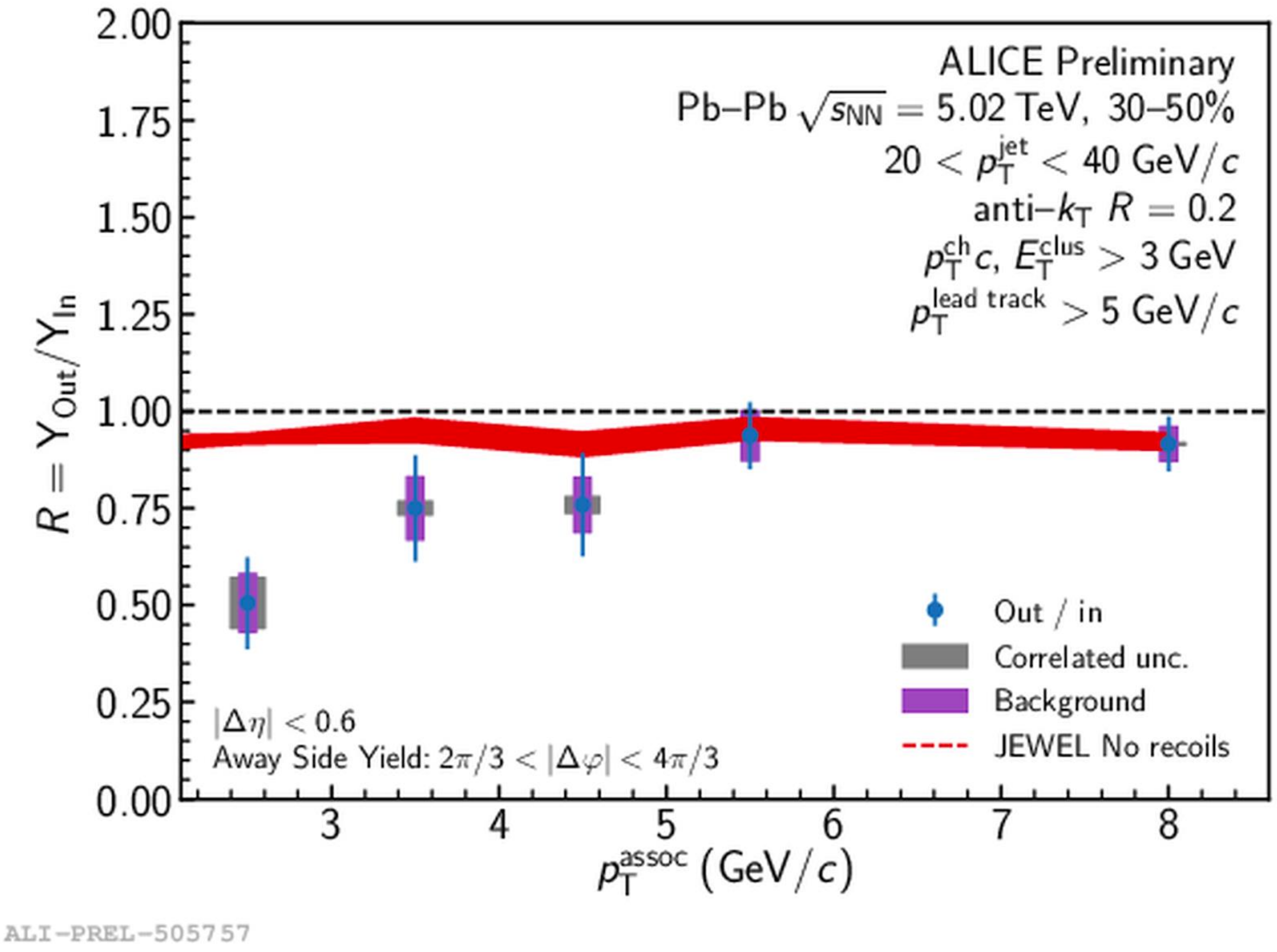
- Pb-Pb $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, 30-50 %
- Track Selection:
  - χ^2 / NDF < 4.0
  - |η| < 0.9
  - p_T > 150 MeV/c
- R = 0.2 anti-k_T (charged + neutral) jets
- 20 GeV/c < p_T^{jet} < 40 GeV/c
  - $p_T^{constit.}$ > 3 GeV/c
  - $p_T^{lead.}$ > 5 GeV/c
- $p_T^{assoc.}$: [0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 10.0] GeV/c

Backup – Ratios Plots

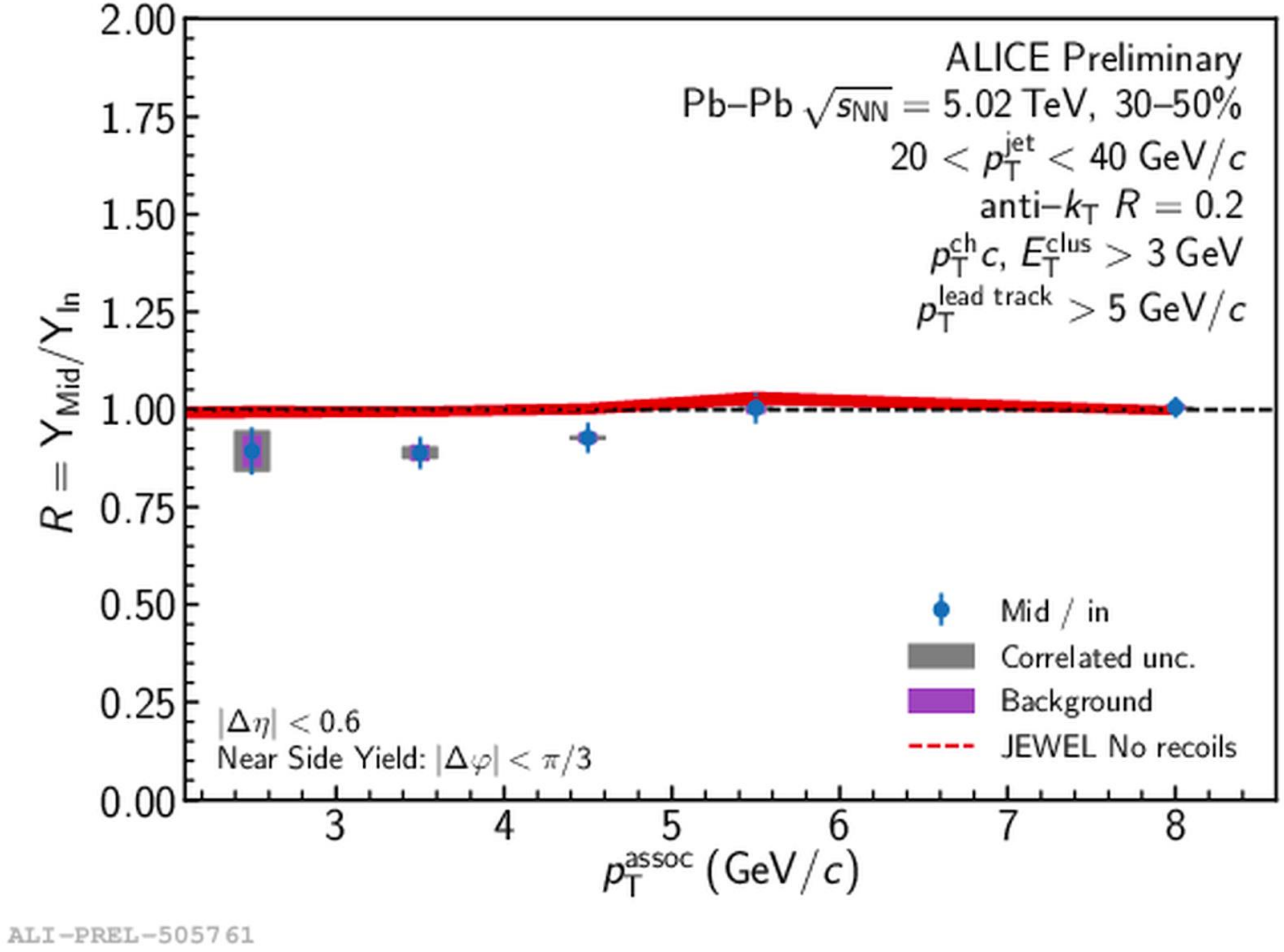


ALI-PREL-505749

Backup – Ratios Plots

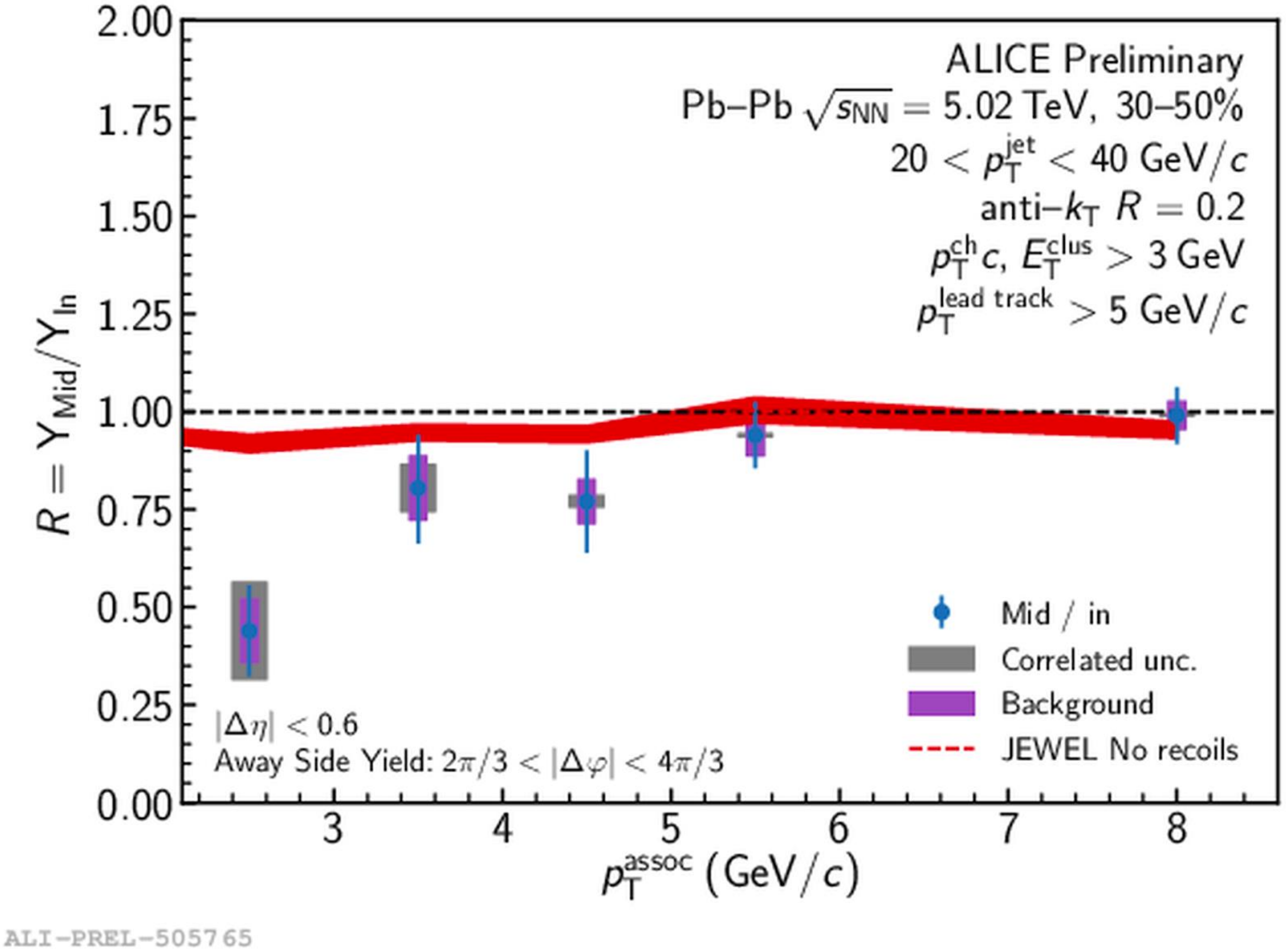


Backup – Ratios Plots



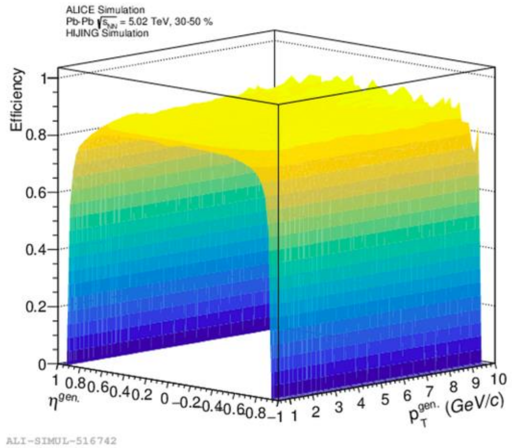
ALICE

Backup – Ratios Plots

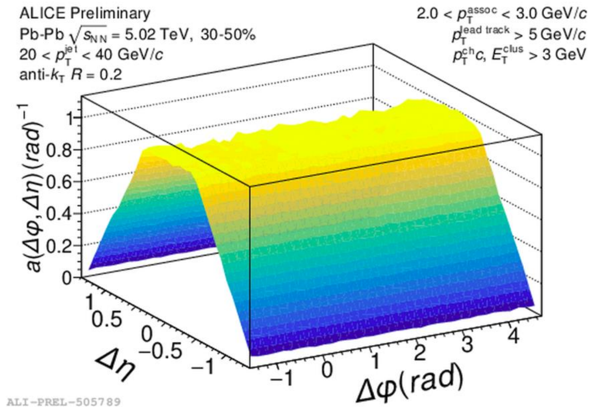


Backup – Acceptance/Efficiency Correction

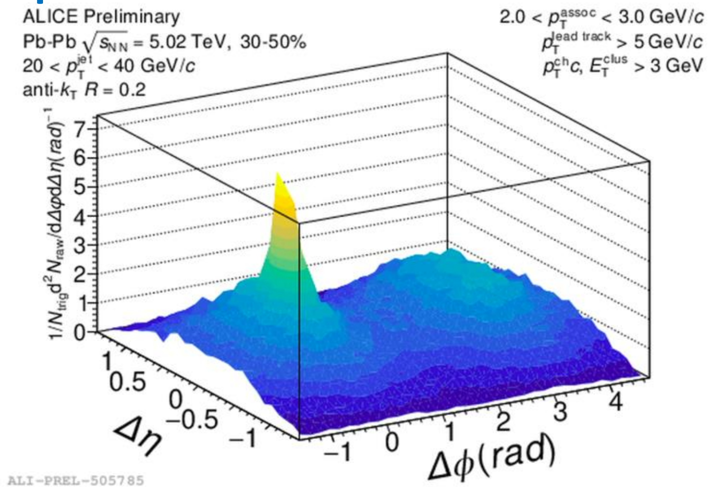
1. Measure correlations, scale by single track reconstruction efficiency



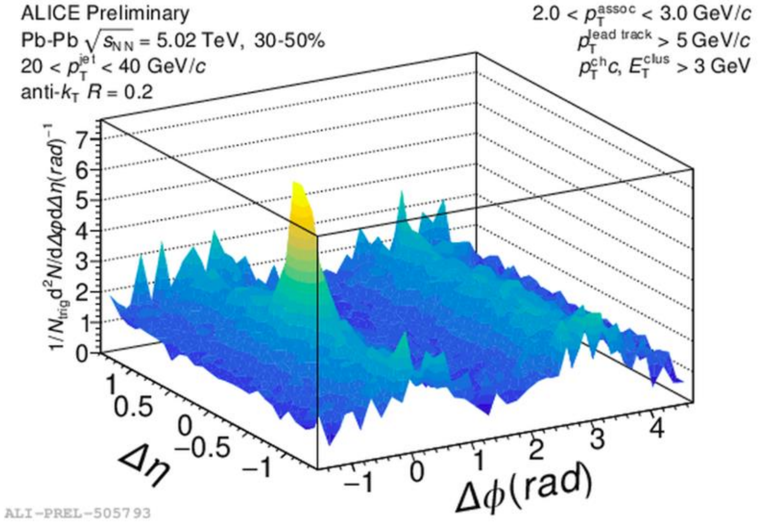
2. Correct for acceptance using mixed events technique (divide raw corr.)



Raw correlation function (scaled by eff.), **in-plane**



Corrected correlation function (scaled by eff.), **in-plane**



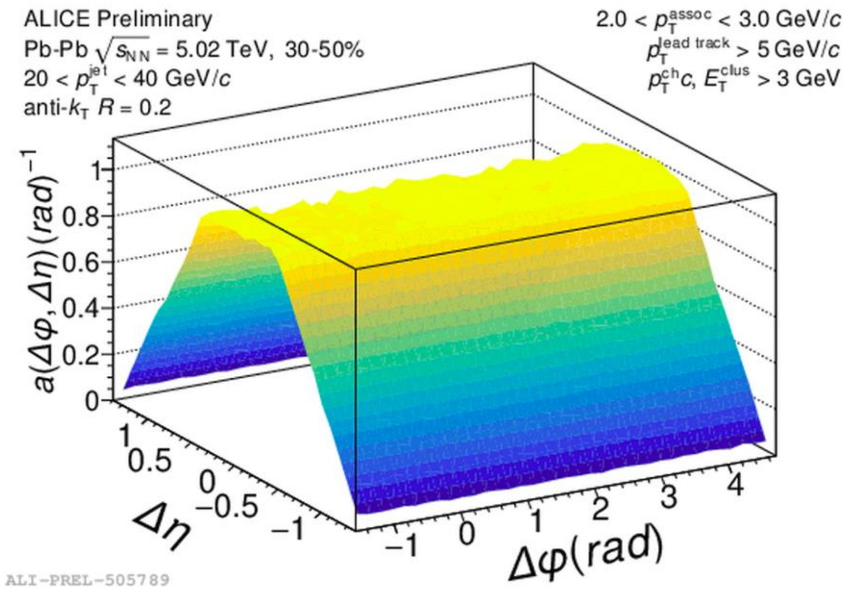
Backup – Systematic Errors – Correlated Scale Uncertainty

- Mixed events used to calculate an acceptance correction

- Results from summing over correlations (mixed and same) binned in z vertex orientation
  - [-10, -8, -6, -4, -2, 0, 2, 4, 6, 8, 10]

- Divide to correct

- Compare to method where sum is of ratios



$$\frac{d^2N^{corrected,meth.1}}{d\Delta\phi d\Delta\eta} = \frac{\sum_{z_{vertex,i}} \frac{d^2N^{un-corrected,z_{vertex,i}}}{d\Delta\phi d\Delta\eta}}{\sum_{z_{vertex,i}} a(\Delta\phi,\Delta\eta)^{z_{vertex,i}}}$$

Numerator – C1

$$\frac{d^2N^{corrected,meth.2}}{d\Delta\phi d\Delta\eta} = \sum_{z_{vertex,i}} \frac{\frac{d^2N^{un-corrected,z_{vertex,i}}}{d\Delta\phi d\Delta\eta}}{a(\Delta\phi,\Delta\eta)^{z_{vertex,i}}}$$

Denominator– C2

Backup – Systematic Errors – Correlated Scale Uncertainty

- α factor constructed based on signal (correlation AFTER subtraction) to background (background fit)

$$\alpha = \frac{\frac{\int_{sig.} C_1}{\int_{bkgd.} C_1}}{\frac{\int_{sig.} C_2}{\int_{bkgd.} C_2}}$$

Numerator – C1

Denominator – C2

- Scale the background term in the RPF by |1 - α|

- This determines the uncertainty on the yields due to the correlated scale uncertainty in determining the acceptance correction

$$\tilde{v}_n^{R,t} = \frac{v_n^t + \cos n\phi_s \frac{\sin nc}{nc} R_n + \sum_{k=2,4,6,\ldots} (v_{k+n} + v_{|k-n|}) \cos k\phi_s \frac{\sin kc}{kc} R_n}{1 + \sum_{k=2,4,6,\ldots} 2 v_k^t \cos k\phi_s \frac{\sin kc}{kc} R_n}$$

$$\tilde{\beta}^R = B \left(1 + \sum_{k=2,4,6,\ldots} 2 v_k^t \cos k\phi_s \frac{\sin kc}{kc} R_n \right)$$

$$\frac{d^2 N^{bkgd.}(\Delta\phi, \Delta\eta)}{d\Delta\phi \, d\Delta\eta} = \pi \tilde{\beta}^R \left(1 + \sum_{n=1}^{\infty} 2 \tilde{v}_n^{R,t} v_n^a \cos n\Delta\phi \right)$$

Backup – Systematic Errors – Background Determination Uncertainty

- Fit done on correlation near side:
  $|\Delta\varphi| < \pi/2$, $0.8 < |\Delta\eta| < 1.2$

$$C(\Delta\varphi,\Delta\eta) = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2 N_{\mathrm{assoc}}}{\mathrm{d}\Delta\varphi\mathrm{d}\Delta\eta} = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2}{\mathrm{d}\Delta\varphi\mathrm{d}\Delta\eta}\frac{N_{\mathrm{meas}}-N_{\mathrm{bkg}}}{\epsilon(p_{\mathrm{T}},\eta)a(\Delta\varphi,\Delta\eta)}$$

- Free Parameters:
  - B – Background level
  - v_2^t
  - v_2^a
  - $v_3^t * v_3^a$
  - v_4^t
  - v_4^a

  (v1t * v1a -> fixed to 0)

$$\frac{d^2N^{bkgd.}(\Delta\phi,\Delta\eta)}{d\Delta\phi d\Delta\eta} = \pi\tilde{\beta}^R\left(1+\sum_{n=1}^{\infty}2\tilde{v_n}^{R,t}v_n^a\cos n\Delta\phi\right)$$

$$\tilde{v_n}^{R,t} = \frac{v_n^t + \cos n\phi_s\frac{\sin nc}{nc}R_n + \sum_{k=2,4,6,\ldots}\left(v_{k+n}+v_{|k-n|}\right)\cos k\phi_s\frac{\sin kc}{kc}R_n}{1+\sum_{k=2,4,6,\ldots}2v_k^t\cos k\phi_s\frac{\sin kc}{kc}R_n}$$

$$\tilde{\beta}^R = B\left(1+\sum_{k=2,4,6,\ldots}2v_k^t\cos k\phi_s\frac{\sin kc}{kc}R_n\right)$$

RPF Background Subtraction:
Sharma et. al. PhysRevC.93.044915

ALICE

Backup – Systematic Errors – Background Determination Uncertainty

- Fit done on correlation near side:
  $|\Delta\varphi| < \pi/2$, $0.8 < |\Delta\eta| < 1.2$

- Free Parameters:
  - B – Background level
  - v_2^t
  - v_2^a
  - $v_3^t * v_3^a$
  - v_4^t
  - v_4^a

  (v1t * v1a -> fixed to 0)

$$\sigma(\Delta\phi) = \sqrt{\sum_i \sum_j \frac{\partial f(\Delta\phi, p_i)}{\partial p_i} \frac{\partial f(\Delta\phi, p_j)}{\partial p_j} \sigma_{i,j}}$$

Derivatives of RPF bkgd. w.r.t. Free params

Covariance Matrix

RPF Background Subtraction:
Sharma et. al. PhysRevC.93.044915